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Effect of Preforming Adherends on Static and Fatigue Strength of Bonded Composite Single-Lap Joints

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SUMMARY

An analytical and experimental investigation was conducted on bonded composite single-lap joints with the adherends preformed to reduce the angle between the line of action of the applied in-plane force and the bondline. A classical closed-form solution was used to analyze the composite joints with various preform angles and overlap lengths. The adherends of the test specimens were preformed before bonding, during the layup and curing process. Static tests were conducted for preform angles of 0°, 5°, 10°, and 15° and overlap lengths of 0.75, 1.75, 2.75, and 3.75 in. A limited fatigue study was conducted for specimens with a 2.75-in. overlap and a preform angle of 5°.

Results of the analysis showed that preforming the adherends of bonded composite single-lap joints significantly reduced the shear and peel stress concentrations in the adhesive. Experimental results showed that preforming the adherends significantly increased their static and fatigue strength and thus increased the load level for which bonded composite single-lap joints can be designed. A 46-percent improvement in static joint strength was obtained by preforming the adherends of a single-lap joint with an overlap length of 3.75 in. Preforming the adherends resulted in an increase in fatigue life of over an order of magnitude for a given load level and a 50-percent increase in the maximum load that bonded composite single-lap joints can transfer for 10^6 cycles.

INTRODUCTION

Bonded joints are potentially the most efficient joints to use with composite materials. However, it has been established (ref. 1) that high peel and shear stress concentrations develop in bonded joints near the ends of the joints. Because composite materials have relatively low interlaminar strength, the high peel and shear stress concentrations usually cause interlaminar adherend failure in the layer or layers close to the faying surface. Several design techniques for reducing the peel and shear stress concentrations to increase the strength of bonded single-lap joints are discussed in references 2 through 7. These techniques include tapering the adherends, adding softening strips to the adhesive, stitching near the edge of the overlap, and preforming the adherends.

The merits of preforming the adherends of single-lap joints were first suggested in references 2 and 3 and were investigated more thoroughly in the analytical and experimental investigation reported in reference 7. The analytical results showed that preforming the adherends of single-lap joints could significantly reduce the peel and shear stress concentrations near the ends of the joint overlaps. Tests conducted on aluminum bonded single-lap joints showed that preforming the adherends significantly increased the static joint strength and fatigue life (ref. 7).

Because of the low interlaminar strength of most composite materials, failure in a composite single-lap joint usually occurs in the first few plies of the adherends due to the large stress concentrations near the ends of the joint overlap. Thus, the reductions in stress concentrations obtained by preforming the adherends should result in significant improvements in the static strength and fatigue life of bonded composite single-lap joints. The analytical and experimental investigation reported

here was undertaken to determine the effects of preforming the adherends on the static and fatigue strength of bonded composite single-lap joints. The variables considered included overlap length and preform angle.

ANALYSIS

Composite single-lap joints with preformed adherends were analyzed using the one-dimensional classical analysis presented in reference 1, modified to account for the preformed adherends (ref. 7). The stresses were assumed to be constant through the adhesive thickness, and the adhesive axial stress parallel to the adherends was assumed to be negligible. Shear deformations in the adherends and the influence of the adhesive on the flexural stiffness of the joint were also assumed to be negligible. The composite adherends and the epoxy adhesive were assumed to be homogeneous, linear elastic materials with the mechanical properties given in the table below.

Parameter	Composite adherends	Epoxy adhesive
Young's modulus, psi	8.1×10^6	0.5×10^6
Poisson's ratio	0.34	0.34

The validity of using the modified classical analysis with the above assumptions was demonstrated in reference 7 for aluminum bonded single-lap joints with preformed adherends. Results obtained using the modified classical analysis were compared with those obtained using finite-element solutions, and the comparison confirmed that the modified classical solution was accurate for qualitative evaluation of the influence of material properties and geometric variations on the shear and peel stresses along the midplane of the adhesive.

EXPERIMENTAL PROCEDURE

Specimens

Seventy-two bonded single-lap-joint specimens were tested in this investigation. Specimen dimensions are given in figure 1 and table I. The adherends consisted of 16-ply T300/5208[1] graphite/epoxy material in a pseudo-isotropic layup $((0°, \pm 45°, 90°)_{2s})$. The nominal adherend thickness was 0.095 in. Specimens with preform angles of 0°, 5°, 10°, and 15° and overlap lengths of 0.75, 1.75, 2.75, and 3.75 in. were tested. The adherends were 2 in. wide and extended 5 in. from the preform point. Fiberglass end tabs 16 plies thick were bonded onto each end of the specimens, as shown in figure 1. The test joints and end tabs were bonded using EA 934[2] epoxy adhesive.

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[1]Thornel 300 (T300) graphite fiber is manufactured by Union Carbide Corporation; 5208 epoxy resin is manufactured by Narmco Materials, a subsidiary of Celanese Corporation.

[2]EA 934 epoxy adhesive is manufactured by the Hysol Division of the Dexter Corporation.

The specimens were made by laying up the adherend material in large sheets on a cald plate bent to the proper preform angle. The radius of the bend in the cald plate was 1.0 in. Adherend segments were cut from the sheets and bonded and cured at room temperature, as prescribed by the adhesive manufacturer. The adhesive bond thickness was controlled by mixing glass beads with the adhesive. Typical specimens are shown in figure 2.

Tests

All specimens were tested in a hydraulically actuated universal test machine. The specimens were mounted using wedge action tension grips with universal joints above and below the grips to ensure that extraneous moments were not applied to the specimen. At the start of each test, the distance between the grips was 5.0 in. plus the overlap length. Both static and limited fatigue tests were conducted on the preformed-adherend bonded specimens. (See table I.) For the static tests, at least three replicate specimens were tested for each configuration. Fatigue tests were conducted on an additional 10 baseline specimens and on 9 specimens with preform angles of 5°. The fatigue specimens each had an overlap length of 2.75 in.

For the static tests, the lap-joint specimens were loaded to failure in tension. The tests were conducted at a constant displacement rate of 0.05 in/min. The fatigue tests were conducted by sinusoidally cycling the load between 10 percent of the average static ultimate tensile strength of the joint and the maximum cyclic tensile test load. The tests were conducted with the machine in a load control mode at a rate of 300 cycles/min.

RESULTS AND DISCUSSION

Analytical Results

Typical analytical results are shown in figure 3 for bonded composite single-lap joints with preformed adherends. Shear and peel stress distributions are shown along the centerline of the adhesive for joints with an overlap length (2c) of 1.00 in. and for preform angles of 0°, 5°, 10°, 15°, and 20°. The shear stresses (fig. 3(a)) were normalized by the average shear stress in the adhesive, and the peel stresses (fig. 3(b)) were normalized by the average tensile stress in the nonoverlap portion of the adherends. Large shear and peel stress concentrations were obtained at the edges of the overlaps for the straight-lap joint (preform angle $\theta = 0$). The shear stress concentration was over 5 times the average adhesive shear stress.

Preforming the adherends reduced both the shear and peel stress concentrations. For a preform angle of approximately 15°, the shear stresses became almost uniform along the adhesive centerline and the peel stresses were slightly compressive at the edges of the joint. Thus, for the given configuration and design load, a preform angle of approximately 15° should result in a joint with an almost uniform stress distribution in the adhesive and a maximum ultimate strength for the joint.

Parametric studies were made for composite single-lap-joint configurations with various adherend and adhesive properties, loads, and overlap lengths. Preforming the adherends resulted in large reductions in the shear and peel stress concentrations for each of the configurations considered. The effects of load, adherend and adhesive stiffness, adherend and adhesive thickness, and overlap length on the optimum preform angle are given in reference 7 and are not repeated here. The optimum

preform angle is defined in reference 7 as the preform angle that results in a minimum value when the Von Mises failure criterion is applied. Because the single-lap problem is geometrically nonlinear, the optimum preform angle is highly dependent on the load assumed in the calculations and cannot be predicted without knowing the ultimate strength of the joint, which is, in turn, dependent on the preform angle.

Experimental Results

Static test results.- A summary listing of the static test results is given in table II. Average results for each overlap length are presented in figure 4, which shows the normalized failure load as a function of the preform angle. The failure loads for each overlap length were normalized by the average failure load for the baseline ($\theta = 0°$) single-lap-joint specimens with the same overlap length. Preforming the adherends resulted in an increase in the ultimate joint strength for each overlap length. An increase in joint strength of 46 percent was obtained for specimens with a 3.75-in. overlap. In general, the improvements in ultimate strength which resulted from preforming the adherends increased with increasing overlap length. One exception was the 2.75-in-overlap specimens, which showed a lower improvement in failure load than was obtained for the 1.75-in-overlap specimens. This inconsistency probably occurred because the 2.75-in-overlap specimens had the highest baseline joint strength.

The preform angle that resulted in the largest improvement in joint strength became smaller as overlap length increased. (That is, the maximum strength for the 0.75-in-overlap specimens occurred for a preform angle of 15°, whereas the maximum strength for the 3.75-in. overlap occurred for a preform angle of 5°.) This reduction in preform angle with increased overlap length is consistent with the analytical results given in reference 7 for aluminum adherends. It also seems to confirm the results presented in figure 3, which indicate that a preform angle of 15° gives the lowest peel and shear stress concentrations and thus should give the highest joint strength for the composite joint with a 0.75-in. overlap. However, as was noted in the previous section, the geometric nonlinearity of the problem makes it impossible to analytically predict the optimum preform angle without knowing the ultimate joint failure load.

The variation of maximum failure load with overlap length is shown in figure 5. The preform angle that gave the maximum failure load varied with overlap length, as shown in the figure. The maximum failure loads were nondimensionalized by the failure load for the baseline ($\theta = 0°$) 0.75-in-overlap specimens. The vertical lines represent the range of measured data and the curves are faired through an average of the data. For the baseline lap joints, increasing the overlap length increased the failure load for overlap lengths up to 2.75 in., but the 3.75-in-overlap specimens showed slightly lower failure loads than the 2.75-in. specimens. Due to the small number of specimens tested (five for the 2.75-in. overlap and three for the 3.75-in. overlap), the difference between the failure loads for the 2.75-in- and 3.75-in-overlap specimens was not statistically significant. Attempts to compare these results with published lap joint data did not reveal any experimental data for overlaps that were longer than those tested here. Thus, it cannot be established if the failure loads reach a peak and then reduce for larger overlap lengths or if they approach a constant value for longer overlaps.

For specimens with the adherends preformed to the optimum angle (the angle that gave the highest experimental failure load), improvements in joint strength with increased overlap length were obtained for overlaps up to 3.75 in. Further tests

with longer overlaps are needed to determine the ultimate improvements in joint strength which are possible by preforming the adherends and increasing the overlap length.

Typical failure modes for the preformed-adherend specimens are shown in figure 6. For the preformed-adherend specimens, interlaminar failure occurred in the first few plies of the adherend, just as it did for the baseline specimens. For the preformed-adherend specimens with longer overlaps, high deformation energy in the joint often resulted in almost complete delamination of the adherends once failure occurred. In a few cases, for specimens that had long overlaps and preform angles larger than were required to give the maximum strength, failure occurred in the adherend at the preform bend. A photograph of a failure in the adherend at the bend is shown in figure 7. This type of failure did not occur for preform angles near or smaller than the angle that gave the maximum failure load.

Experimental results reported in reference 7 indicated that preforming the adherends of aluminum bonded joints with dimensions similar to those of the composite joints investigated in this study resulted in an improvement of up to 120 percent in the strength of aluminum joints, compared with a maximum improvement of 46 percent obtained in the tests described here for preformed-adherend composite joints. The bonded aluminum joints failed in the adhesive for all preform angles. As was noted above, the composite preformed-adherend joints experienced interlaminar failure in the first few plies of the adherend for all preform angles. It had been anticipated that the large reduction in peel stress concentration calculated for the preformed-adherend joints would result in the failure shifting from the adherend to the adhesive. This shift should have produced an even larger increase in joint strength than that obtained for the aluminum joints. Thus, the smaller improvement in composite joint strength with preform angle compared with that obtained for aluminum joint strength is probably because the composite joint failures always occurred in the adherends. Also, because the analysis only predicted stress in the adhesive, the analytical results did not relate directly to those obtained experimentally for the composite adherend failures.

Cyclic fatigue results.- The results of the fatigue study are shown in figure 8. The maximum cyclic load is shown as a function of the number of cycles to failure for the baseline configuration and for a configuration with a 5° preform angle. The fatigue tests were conducted on specimens with an overlap length of 2.75 in. Each symbol represents one test except for those that indicate the static results at one cycle; these represent an average value for the specimens tested. Preforming the adherend resulted in approximately a 25-percent increase in the static strength and an improvement of over an order of magnitude in the fatigue life for each load level. The runout load (the load for which the fatigue life was greater than 10^6 cycles) for the preformed-adherend configuration was at least 50 percent higher than the runout load for the baseline configuration. Preforming the adherends of aluminum bonded single-lap joints was reported in reference 7 to give larger improvements in fatigue life (an increase of several orders of magnitude) and load range (100-percent increase) than were obtained in the present study for composite single-lap joints. Because most bonded joints are subjected to cyclic loading, preforming the adherends can significantly increase the load range for which bonded single-lap joints can be used.

CONCLUDING REMARKS

An analytical and experimental investigation was conducted on bonded composite single-lap joints with the adherends preformed to reduce the angle between the line of action of the applied in-plane force and the bondline. A classical closed-form solution was used to analyze the composite joints with various preform angles and overlap lengths. The adherends of the test specimens were preformed before bonding, during the layup and curing process. Static tests were conducted for preform angles of 0°, 5°, 10°, and 15° and overlap lengths of 0.75, 1.75, 2.75, and 3.75 in. A limited fatigue study was conducted for specimens with a 2.75-in. overlap and a preform angle of 5°.

Results of the analysis showed that preforming the adherends of bonded composite single-lap joints significantly reduced the shear and peel stress concentrations in the adhesive. Experimental results showed that preforming the adherends significantly increased the static and fatigue strength and thus the load level for which bonded composite single-lap joints can be applied. A 46-percent improvement in static joint strength was obtained by preforming the adherends of a single-lap joint with an overlap length of 3.75 in. The improvement in ultimate static strength due to preforming the adherends became greater with longer overlaps and the preform angle that resulted in the maximum static joint strength decreased with increasing overlap length.

Preforming the adherends resulted in an increase of over an order of magnitude in fatigue life for a given load level and increased by 50 percent the maximum load that bonded composite single-lap joints could transfer for 10^6 cycles. However, the improvements in fatigue life and load range obtained for composite joints were not as great as those shown previously for aluminum joints with preformed adherends. This was probably because the composite joints always failed in the adherends, whereas the aluminum joints failed in the adhesive. Because the analysis only predicted stresses in the adhesive, the analytical results did not relate directly to the failures in the adherend obtained for the composite joints.

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TABLE I.- SPECIMEN TEST PARAMETERS

Test type	Overlap length, in.	Preform angle, deg	No. of specimens
Static	0.75	0 5 10 15	3 3 3 3
	1.75	0 5 10 15	3 3 3 3
	2.75	0 5 10 15	5 6 3 3
	3.75	0 5 10 15	3 3 3 3
Fatigue	2.75	0 5	10 9

TABLE II.- SUMMARY OF STATIC TEST RESULTS

Overlap length, in.	Ultimate load, lb, for a preform angle of -			
	0°	5°	10°	15°
0.75	3950 4025 4000	4 250 3 750 4 350	4 750 4 500 4 800	4925 4400 4800
1.75	6850 6400 6800	8 725 9 950 8 400	10 020 8 200 9 350	7000 6400 6850
2.75	8020 8800 7950 8000 9510	11 400 10 975 11 100 10 530 10 870 9 920	8 200 9 852 8 050	5100 4400 6100
3.75	8700 8325 6850	11 500 11 700 11 550	*8 600 *9 000 8 800	*6900 *6000 *6800

*Failure in adherend at preform bend.

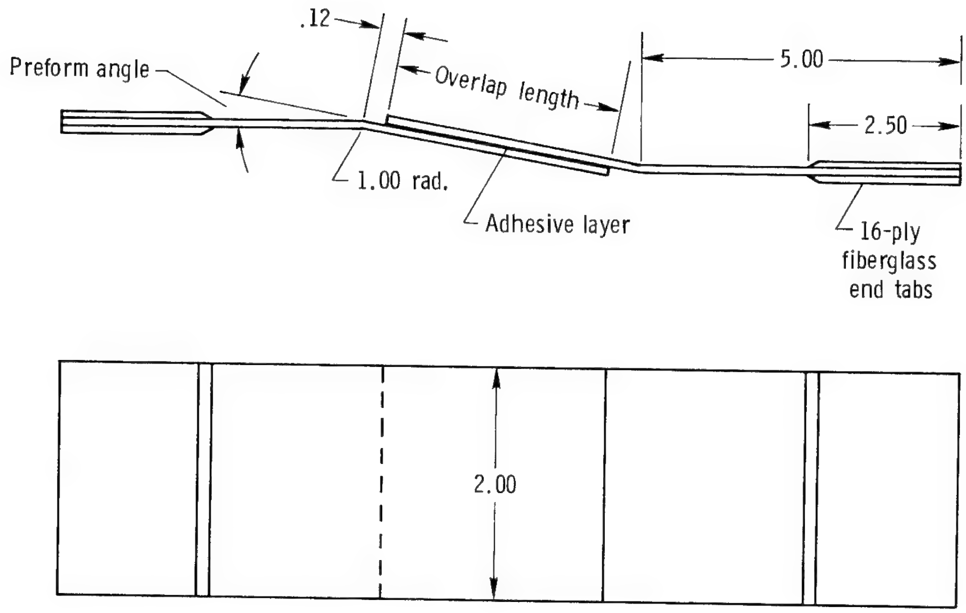

Figure 1.- Schematic of preformed-adherend test specimens.
Dimensions in inches.

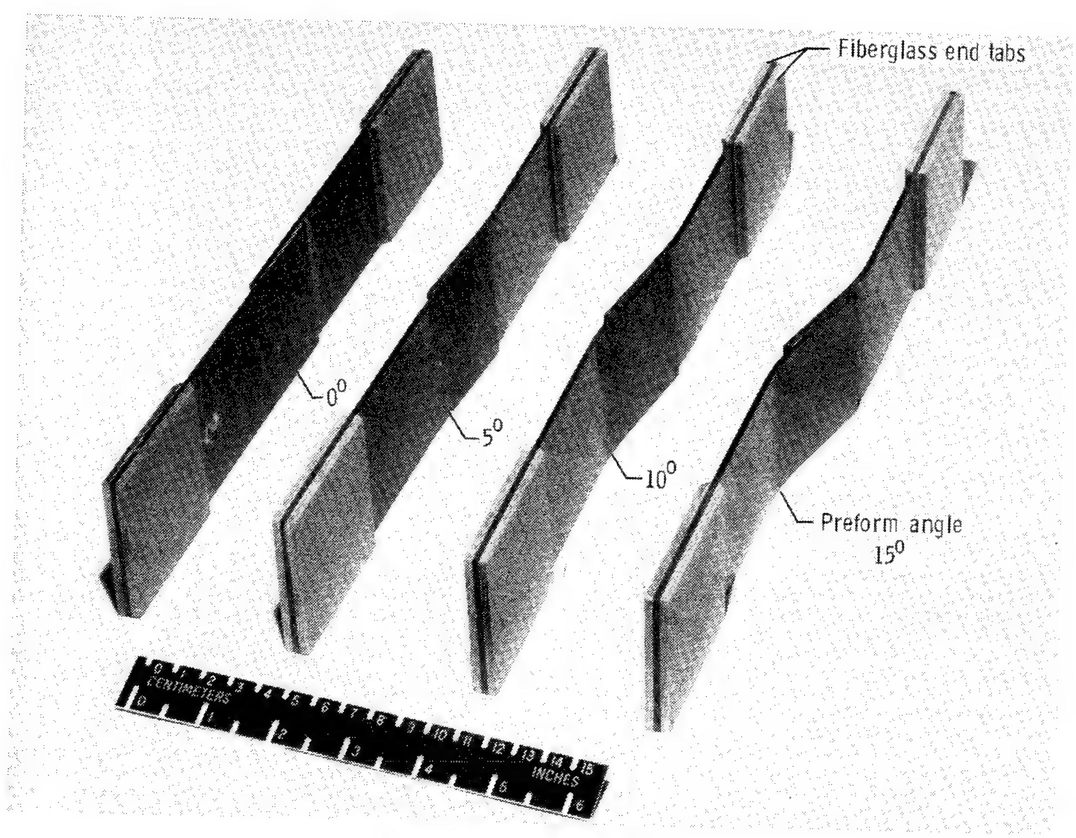

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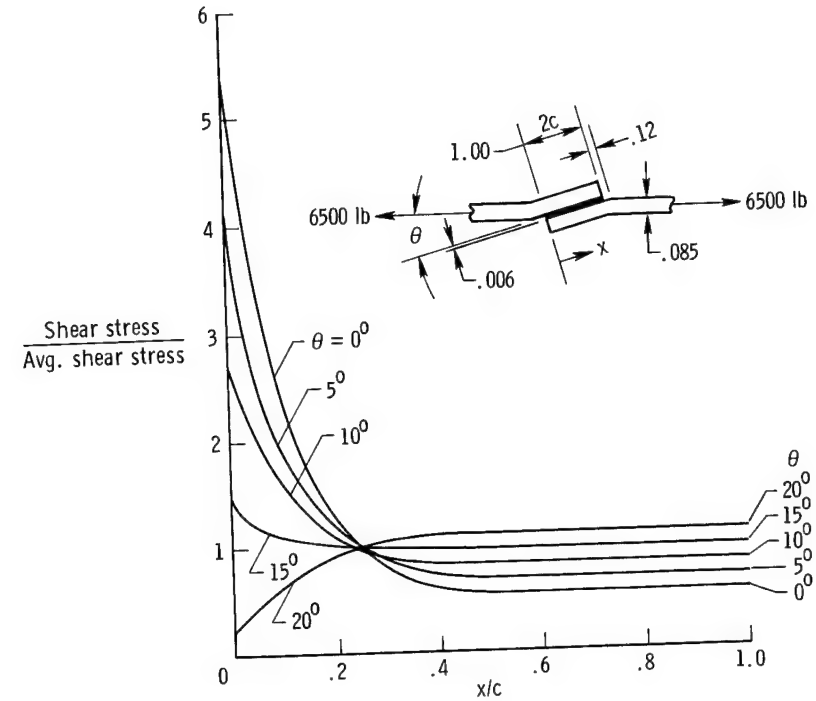
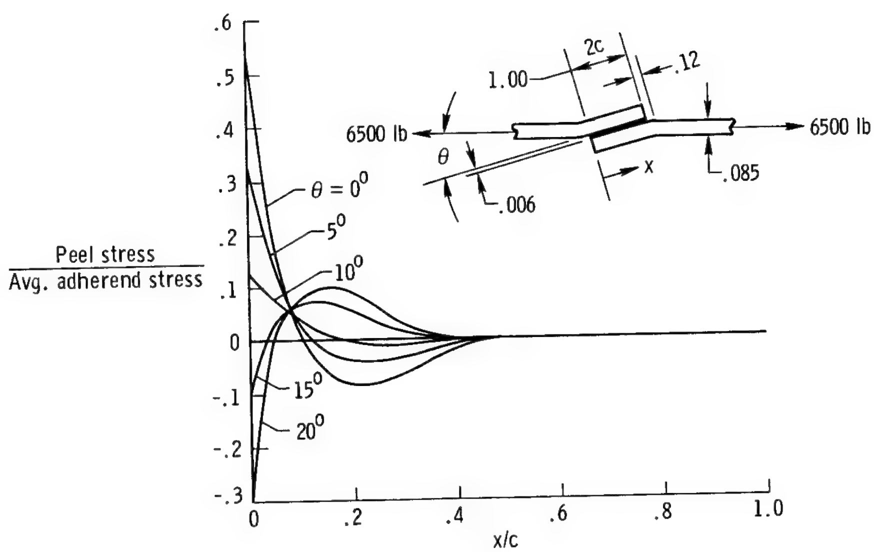
Figure 2.- Typical preformed-adherend test specimens.
Overlap length = 1.75 in.



(a) Shear stress.



(b) Peel stress.

Figure 3.- Effect of preform angle on stress distribution in center of adhesive for bonded composite single-lap joint. Dimensions in inches.

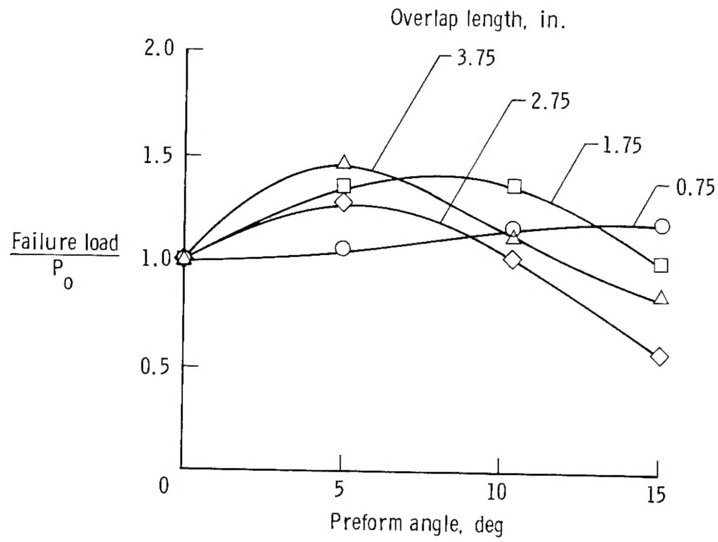


Figure 4.- Effect of preform angle on average failure load. P_o = Average failure load of baseline joint with overlap indicated.

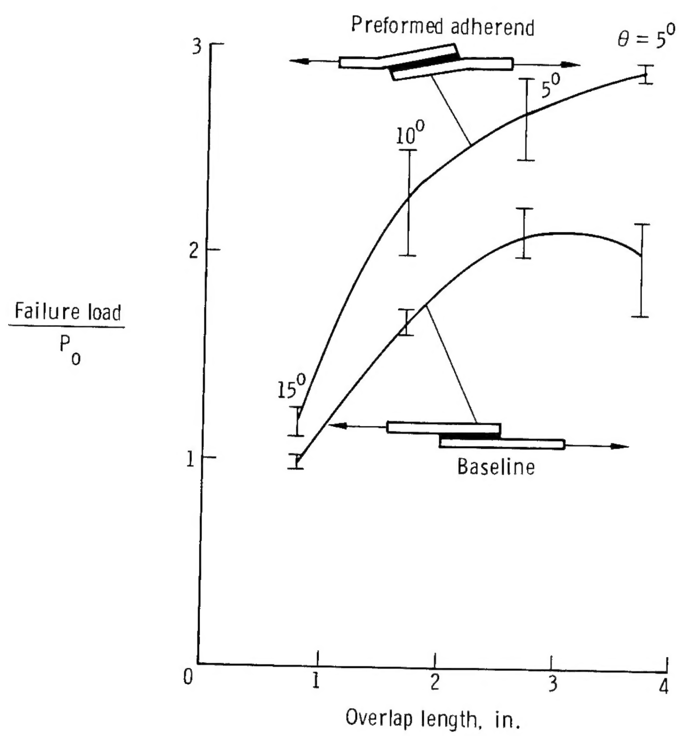


Figure 5.- Maximum failure load as a function of overlap length for baseline and preformed-adherend joints. P_o = Average failure load for baseline joint with 0.75-in. overlap.

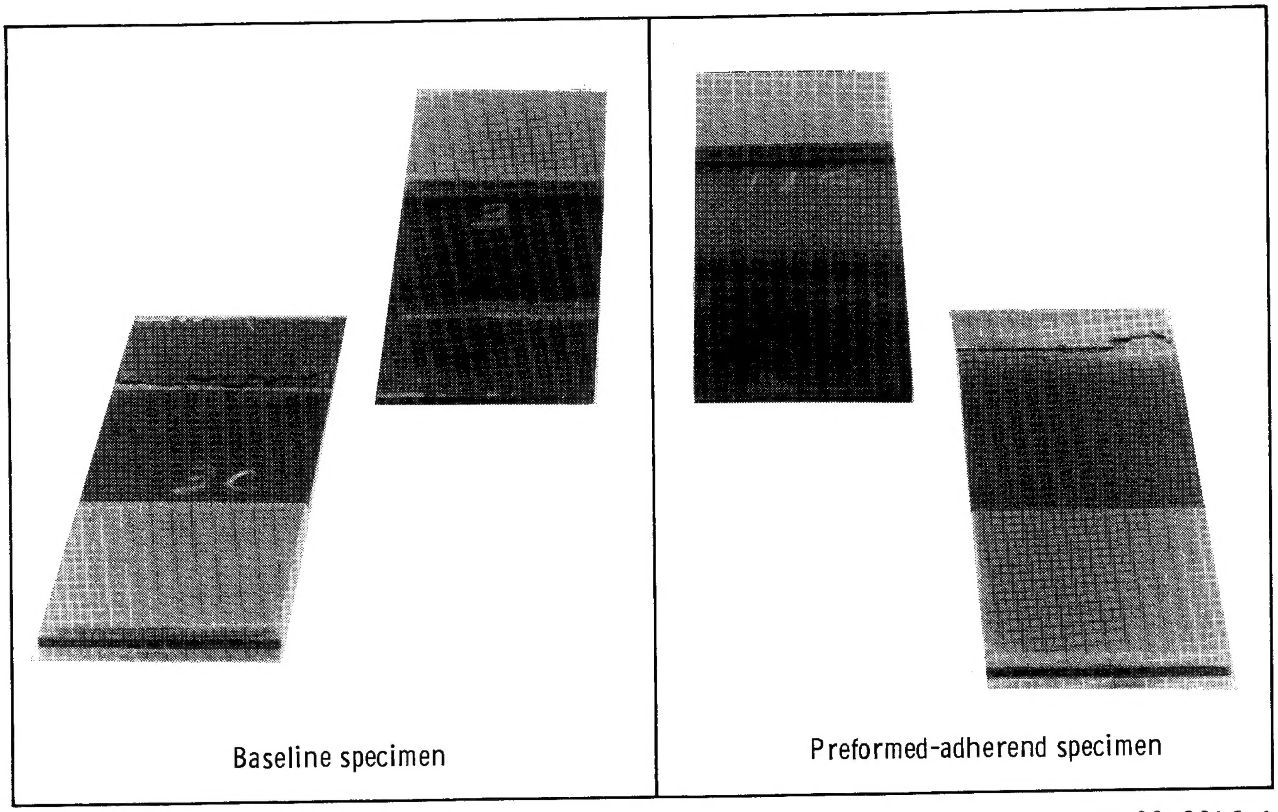


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Figure 6.- Typical joint failure for baseline and preformed-adherend composite joints.

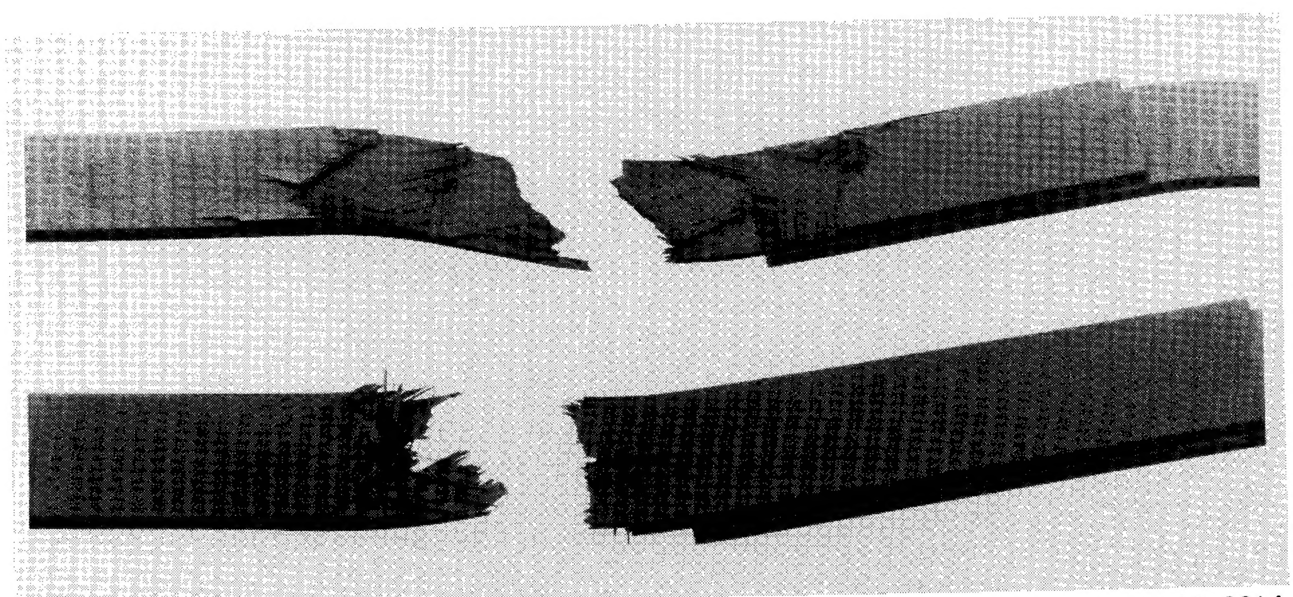

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Figure 7.- Failure at bend in preformed-adherend composite joints.

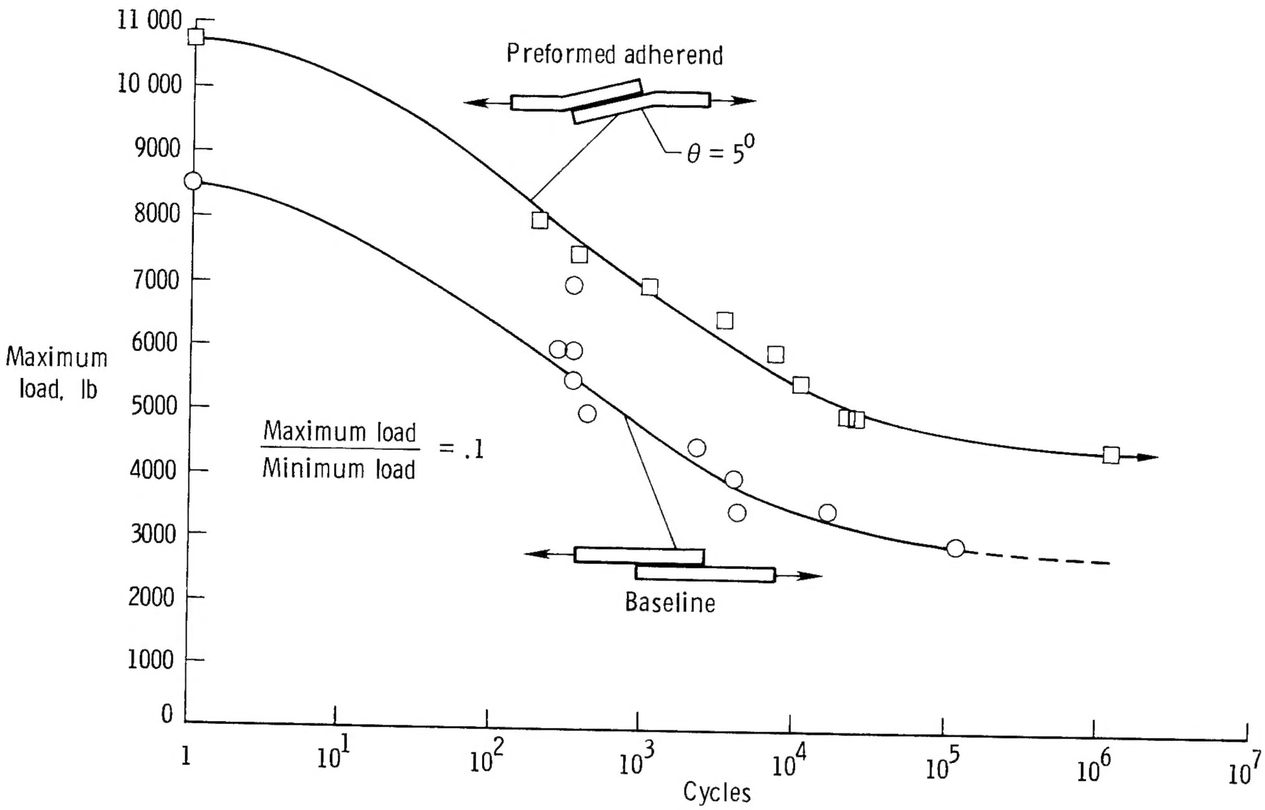

Figure 8.- Fatigue characteristics of baseline and preformed-adherend composite joints. Overlap length = 2.75 in.

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15. Supplementary Notes

16. Abstract

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